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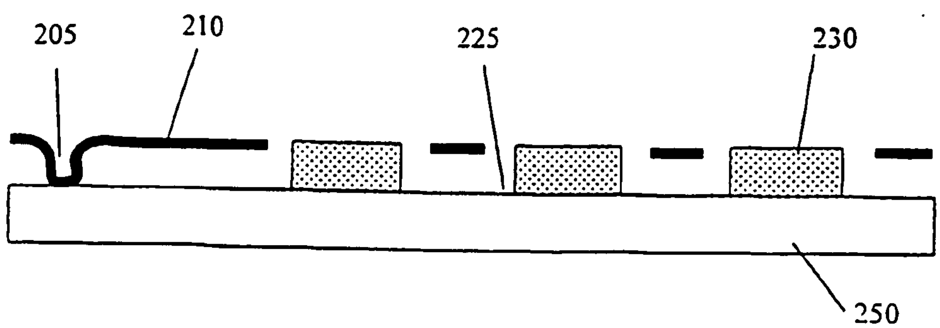
(54) Title: POLARIZATION INDEPENDENT GRATING MODULATOR



(57) Abstract: A fiber-optic modulator based on a micromachined grating device which is both polarization independent and achromatic in behavior is described. The device is a two dimensional grating or periodic structure which is symmetric in the X and Y axes. It is comprised of a membrane (210) with holes cut in it that moves downward with the application of a voltage which starts diffracting light. The hole region may have a raised island (230) to provide achromatic behavior.

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POLARIZATION INDEPENDENT GRATING MODULATOR

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to polarization independent grating modulator. More particularly, the present invention relates to micromachined grating modulators which exhibit polarization independent behavior.

Description of Related Art

Optical modulators are an important component in optical systems for controlling and modulating light. In particular, for fiber-optic networks, modulators are used for imparting data modulation on the transmitting laser beam and as an electronically controlled variable optical attenuator (VOA) for channel equalization and power control. In fiber-optic networks the state of polarization is unknown and therefore little or no polarization dependence is tolerated from components.

Bloom et al. (patent no. 5,311,360) demonstrated a micromachined grating modulator comprised of narrow ribbons anchored at the two ends but suspended in the center $\lambda/2$ (half wavelength) above the substrate. The ribbons are separated by gaps of the same width. Both ribbon and gap have a reflective coating from which light is reflected in phase and therefore it emulates a mirror. By applying a voltage to the ribbons, the electrostatic force moves the ribbon down by $\lambda/4$. Now the ribbon and gap are out of phase and all the light is diffracted out in multiple orders. Thus modulation is achieved.

One limitation of the previous invention is that the height difference between the ribbon and gap leads to poor spectral performance. Bloom et al. (patent no. 5,841,579) improved on this by inventing a flat grating light valve comprised of ribbons of equal width with very little gap between them. In the nominal position, all ribbons are at the same height. By applying a voltage and pulling every other ribbon down, the grating is turned on.

For fiber-optic applications operating over the bandwidth of erbium doped fiber amplifier (EDFA), the spectral performance of the previous invention is not acceptable especially at high attenuation. Godil et al. (Achromatic optical modulator, patent application Serial No. 09/372,649, filed August 11, 1999) demonstrated a device with alternate narrow and wide ribbon. By proper choice of the ribbon widths and gap width, spectrally flat attenuation over the EDFA band over a large dynamic range is obtained.

A limitation of the previous inventions, because of lack of symmetry, is that they are not completely polarization independent. In particular, at high attenuation the polarization dependence is unacceptably high for fiber-optic networks.

What is needed is a micromachined modulator which exhibits achromatic and polarization independent behavior.

SUMMARY OF THE INVENTION

The present invention is directed towards a fiber-optic modulator comprising of an input optical fiber carrying a light beam through a lens onto a micromachined reflective modulator, back through the lens into an output optical fiber. The micromachined modulator is a two dimensional grating or periodic structure which is modulated by the application of a voltage. The two dimensional grating is symmetric in the X and Y axes, and therefore leads to polarization independent behavior. The achromatic modulator invention of Godil (patent application filed 8/99) is also incorporated to give achromatic behavior.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a fiber-optic modulator comprised of a micromachined grating device of the present invention

FIG. 2A-2B show the plan view and cross-sectional view of the micromachined grating device in the preferred embodiment

FIG. 3A-3B show the plan view and cross-sectional view of the micromachined grating device in the alternate embodiment with square holes and islands.

FIG. 4A-4B show the plan view of the micromachined grating device in the alternate embodiment without achromatic compensation.

FIG. 5A-5H show a process for fabricating the micromachined grating device.

DETAILED DESCRIPTION OF THE INVENTION

FIGURE 1 shows the fiber-optic micromachined modulator 100 comprised of input fiber 110 and output fiber 112 held in a double bored ferrule 120. Light from the input fiber 110 is collimated by lens 130, impinges on the micromachined device 200, reflects and is focused into the output fiber 112. By applying a voltage to the device 200, light is diffracted in a two-dimensional pattern and the through light in the output fiber is reduced. Thus modulation and attenuation function is achieved.

It is desirable to achieve the modulation function in an achromatic and polarization independent way. The device 200 which accomplishes this is shown in FIGURES 2A, 2B with a plan view and cross-sectional view respectively. The device is comprised of round islands 230 of height h and a membrane 210 which is anchored 205 all around with round holes 220 cut in it. The ring region 225 is formed between the island and the membrane. Release holes 240 in the membrane facilitate the release or etch of the sacrificial layer under the membrane.

Device 200 is periodic in X and Y with a period Λ which is typically in the 20 to 200 micron range. The device is symmetrical in X and Y, and therefore leads to polarization independent behavior. The island 230 has a height h which is $m\lambda/2$, where m is an integer and λ is the wavelength of light. Typically m is 3 and for λ=1.55 μm, h is 2.32 μm. The island may be made of silicon, poly silicon, oxide, silicon nitride or it may be silicon covered with oxide or nitride. The top surface of the membrane 210 is nominally coplanar with the islands. The membrane is anchored down to the substrate 250 at

discrete anchor points 205. The design of the anchor may be more elaborate for a more rigid anchoring. The substrate 250 may be a silicon wafer, quartz wafer, glass plate, or any other suitable material. The membrane film is tensile which keeps it suspended. The membrane may be silicon nitride, poly silicon, oxide, aluminum, or some other suitable material. The holes 220 in the membrane are larger than the islands. The whole device is covered with a blanket evaporation of aluminum or gold. For h=2.32 μm, light reflected from the ring region 225 between the island and the membrane is 6π out of phase with respect to the island and the membrane. Therefore the device looks like a mirror in this state which is the on state for the modulator. When a voltage is applied to the membrane, electrostatic force moves the membrane downwards and the device starts diffracting light in a two-dimensional pattern. To achieve full extinction, when the membrane is moved λ/4, it is necessary that the membrane area be equal to the area of the island and the ring region 225. In addition, the invention of Godil (Achromatic optical modulator, filed 8/99) teaches that to obtain achromatic behavior the area of the ring region should be 1/(2m) of the membrane area. For this particular case, it is $1/6^{th}$.

Another variation of the device 200' is to have square islands and square holes in the membrane as shown in FIGURES 3A, 3B. Now the device does not require release holes and is easier to layout. All other considerations and explanations apply equally here as described in the previous paragraph. Other island and hole shapes are also possible.

Another variation of the device, if achromatic behavior is not important, is not to have the islands as shown in FIGURES 4A, 4B. The device is now simpler with one reduced processing/masking step. To achieve full extinction, the area of the membrane 410 should be equal to the area of the holes 430 in the membrane. Anchors 405 are similarly designed and release holes 440 serve the same function. The top surface of the membrane is mλ/2 above the substrate, where m is typically 3 or 4.

Process and device fabrication of the preferred embodiment shown in FIGURE 2 is now described. The process flow is shown in FIGURE 5A-5H starting with a silicon wafer 250. The first lithography mask defines the islands

230 which emerge after the silicon is etched down 2.32μm with RIE (reactive ion etching) as shown in FIGURE 5B. This is followed by growing a thin thermal oxide 235 in the range of 200-600 angstroms. LPCVD polysilicon or amorphous silicon 245 is deposited next as the sacrificial layer. It is important that the poly or amorphous silicon be optically smooth. The polysilicon is patterned and etched down to the oxide to define the anchors 205 as shown in FIGURE 5E. Sacrificial layer 245 may be PSG (phospho-silicate glass) or some other oxide, which is removed using hydrofluoric acid. Sacrificial layer 245 may also be a polymer, which is removed using an oxygen plasma etch. This is followed by depositing LPCVD silicon nitride 255 as the mechanical layer. The silicon nitride may be stoichiometric or silicon rich. The silicon nitride is defined and etched after patterning the photoresist 265. Xenon difluoride etch is used to remove the polysilicon or amorphous silicon sacrificial layer. Finally the photoresist 265 is removed with an oxygen plasma etch followed by a blanket aluminum or gold evaporation.

The foregoing description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously, many modifications and variations will be apparent to practitioners skilled in this art.

IN THE CLAIMS:

1. A controllable grating, comprising:

a substrate with at least a portion being substantially reflective;

a membrane with a front surface, a back surface, the membrane including a plurality of first apertures extending from the front to the back surface, at least a portion of the front surface being substantially reflective;

at least one anchor coupling the membrane and the substrate at a first distance in a passive state, wherein in an active state an application of a force to the membrane modifies the first distance and provides a controllable diffraction of light that is incident on the substrate and the membrane.

2. The grating of claim 1, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned to provide diffraction of the light incident on the membrane and substrate that is selectably independent of a polarization state of the light incident on the membrane and substrate.

3. The grating of claim 1, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned sufficiently symmetrically along the X and Y axes to provide diffraction of the light incident on the membrane and substrate that is selectably independent of a polarization state of the light incident on the membrane and substrate.

4. The grating of claim 3, wherein the positioning of the plurality of first apertures is symmetric along the X and Y axes.

5. The grating of claim 1, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned sufficiently periodically along the X and Y axes to provide a controllable diffraction of the light incident on the membrane and substrate with a desired magnitude.

6. The grating of claim 4, wherein positioning of the plurality of first apertures is periodic along the X and Y axes.

7. The grating of claim 1, wherein the force is an electrostatic force.

8. The grating of claim 7, wherein the electrostatic force is generated by an applied voltage.

9. The grating of claim 8, wherein the voltage includes an alternating current component.

10. A two-dimensional controllable grating, comprising:

a substrate with at least a portion being substantially reflective;

a plurality of islands coupled to the substrate, at least a portion of the plurality of islands being substantially reflective;

a membrane with a front surface, a back surface, the membrane including a plurality of first apertures extending from the front to the back surface, each of an island corresponding to a first aperture, at least a portion of the front surface being substantially reflective;

at least one anchor coupling the membrane and the substrate at a first distance in a passive state, wherein in an active state an application of a force to the membrane modifies the first distance and provides a controllable diffraction of light that is incident on the substrate and thc membrane.

11. The grating of claim 10, wherein the force is an electrostatic force.

12. The grating of claim 11, wherein the electrostatic force is generated by an applied voltage.

13. The grating of claim 12, wherein the voltage includes an alternating current component.

14. The grating of claim 10, wherein at least a portion of the plurality of islands are integrally formed with at least a portion of the substrate.

15. The grating of claim 10, wherein all of the plurality of islands are integrally formed with the substrate.

16. The grating of claim 10, wherein at least a portion of the plurality of islands are applied to at least a portion of the substrate.

17. The grating of claim 10, wherein all of the plurality of islands are applied to the substrate.

18. The grating of claim 10, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned to provide diffraction of the light incident on the membrane and substrate that is selectably independent of a polarization state of the light incident on the membrane and substrate.

19. The grating of claim 10, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned sufficiently symmetrically along the X and Y axes to provide diffraction of the light incident on the membrane and substrate that is selectably independent of a polarization state of the light incident on the membrane and substrate.

20. The grating of claim 19, wherein the positioning of the plurality of first apertures is symmetric along the X and Y axes.

21. The grating of claim 10, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned sufficiently periodically along the X and Y axes to provide a controllable diffraction of the light incident on the membrane and substrate with a desired magnitude.

22. The grating of claim 19, wherein positioning of the plurality of first apertures is periodic along the X and Y axes.

23. A two-dimensional controllable grating, comprising:

a substrate with at least a portion being substantially reflective;

a plurality of islands coupled to the substrate, the plurality of islands having a total illuminated surface area of A_i, at least a portion of the plurality of islands being substantially reflective;

a membrane with a front surface, a back surface, the membrane including a plurality of first apertures extending from the front to the back surface, each of an island corresponding to a first aperture, the plurality of first apertures having a total illuminated surface area of A_a, and the membrane having a total illuminated surface area A_m, with A_m not including A_a, and an illuminated surface area A_d defined as A_a minus A_i, at least a portion of the first surface being substantially reflective;

at least one anchor coupling the membrane and the substrate at a first distance in a passive state, wherein in an active state an application of a force to the membrane modifies the first distance and provides a controllable diffraction of light that is incident on the substrate and the membrane; and wherein magnitudes of the illuminated surface areas Am, A_i, A_h, and A_d and ratios of the areas A_m, A_i, A_h and A_d are selected to provide a substantially achromatic diffraction of the grating over a wavelength range of light that illuminates the grating.

24. The grating of claim 23, wherein the membrane includes a plurality of second apertures utilized for the processing of the grating, and the illuminated surface area of the plurality of second apertures is defined as $A2_a$.

25. The grating of claim 24, wherein the illuminated surface area A_d is defined as $A2_a$ plus A_a minus A_i.

26. The grating of claim 23 wherein the force is an electrostatic force.

27. The grating of claim 26 wherein the electrostatic force is generated by an applied voltage.

28. The grating of claim 27 wherein the voltage includes an alternating current component.

29. The grating of claim 23, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned to provide diffraction of the light incident on the membrane and substrate that is selectably independent of a polarization state of the light incident on the membrane and substrate.

30. The grating of claim 23, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned sufficiently symmetrically along the X and Y axes to provide diffraction of the light incident on the membrane and substrate that is selectably independent of a polarization state of the light incident on the membrane and substrate.

31. The grating of claim 30 wherein the positioning of the plurality of first apertures is symmetric along the X and Y axes.

32. The grating of claim 23, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned sufficiently periodically along the X and Y axes to provide a controllable diffraction of the light incident on the membrane and substrate with a desired magnitude.

33. The grating of claim 31, wherein positioning of the plurality of first apertures is periodic along the X and Y axes.

34. The grating of claim 23, wherein at least a portion of the plurality of islands are integrally formed with at least a portion of the substrate.

35. The grating of claim 23, wherein all of the plurality of islands are integrally formed with the substrate.

36. The grating of claim 23, wherein at least a portion of the plurality of islands are applied to at least a portion of the substrate.

37. The grating of claim 23, wherein all of the plurality of islands are applied to the substrate.

38. The grating of claim 23, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned to provide diffraction of the light incident on the membrane and substrate that is selectably independent of a polarization state of the light incident on the membrane and substrate.

39. The grating of claim 23, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being

positioned sufficiently symmetrically along the X and Y axes to provide diffraction of the light incident on the membrane and substrate that is selectably independent of a polarization state of the light incident on the membrane and substrate.

40. The grating of claim 39, wherein the positioning of the plurality of first apertures is symmetric along the X and Y axes.

41. The grating of claim 23, wherein the membrane has an X axis and a Y axis defining a membrane plane, the plurality of first apertures being positioned sufficiently periodically along the X and Y axes to provide a controllable diffraction of the light incident on the membrane and substrate with a desired magnitude.

42. The grating of claim 40, wherein positioning of the plurality of first apertures is periodic along the X and Y axes.

43. The grating of claim 23, wherein the first distance is $N\lambda 2$ beneath the membrane, where N is an integer and λ is a center wavelength of the light that illuminates the grating.

44. The element of claim 23, wherein illuminated surface area A_d is 1/(2N) times the area of the illuminated surface area A_m, where N is an integer.

45. A fiber optic component, comprising:

an input optical fiber capable of carrying an optical beam, the input optical fiber having an input optical fiber longitudinal axis and an input optical fiber endface;

a lens optically coupled to the input optical fiber, the lens capable of collimating the optical beam from the input optical fiber, the lens having an optical axis and an input focal plane and an output focal plane;

an output optical fiber optically coupled to the lens, the output optical fiber having an output optical fiber longitudinal axis and an output optical fiber endface; and

a controllable grating optically coupled to the lens, the controllable grating capable of controllably reflecting substantially none to substantially all

of the optical beam from the input optical fiber through the lens, back through the lens and into the output optical fiber, the controllable grating capable of modifying at least one characteristic of the optical beam, the controllable grating having an at least one reflective surface.

46. The component of claim 45, wherein the controllable grating comprises:

a substrate;

a membrane with a front surface, a back surface, the membrane including a plurality of first apertures extending from the front to the back surface;

at least one anchor coupling the membrane and the substrate at a first distance in a passive state, wherein in an active state an application of a force to the membrane modifies the first distance and provides a controllable diffraction of light that is incident on the substrate and the membrane.

47. The component of claim 45, wherein the controllable grating comprises:

a substrate;

a plurality of islands coupled to the substrate;

a membrane with a front surface, a back surface, the membrane including a plurality of first apertures extending from the front to the back surface, each of an island corresponding to a first aperture;

at least one anchor coupling the membrane and the substrate at a first distance in a passive state, wherein in an active state an application of a force to the membrane modifies the first distance and provides a controllable diffraction of light that is incident on the substrate and the membrane.

48. The component of claim 45, wherein the controllable grating comprises:

a substrate;

a plurality of islands coupled to the substrate, the plurality of islands having a total illuminated surface area of A_i;

a membrane with a front surface, a back surface, the membrane including a plurality of first apertures extending from the front to the back surface, each of an island corresponding to a first aperture, the plurality of first apertures having a total illuminated surface area of A_a, and the membrane having a total illuminated surface area A_m, with A_m not including A_a, and an illuminated surface area A_d defined as A_a minus A_i;

at least one anchor coupling the membrane and the substrate at a first distance in a passive state, wherein in an active state an application of a force to the membrane modifies the first distance and provides a controllable diffraction of light that is incident on the substrate and the membrane; and wherein magnitudes of the illuminated surface areas A_m, A_i, A_h, and A_d and ratios of the areas A_m, A_i, A_h and A_d are selected to provide a substantially achromatic diffraction of the grating over a wavelength range of light that illuminates the grating.

49. A method of variable optical attenuation, comprising:

providing a controllable grating with a substrate, a membrane and an anchor that couples the membrane and the substrate at a first distance in a passive state;

applying a force to the membrane;

modifying the first distance by the application of the force; and

providing a controllable diffraction of light that is incident on the substrate and the membrane.

50. The method of claim 49, wherein the force is an electrostatic force.

51. The method of claim 50, wherein the electrostatic force is generated by an applied voltage.

52. The method of claim 51, wherein the voltage includes an alternating current component.

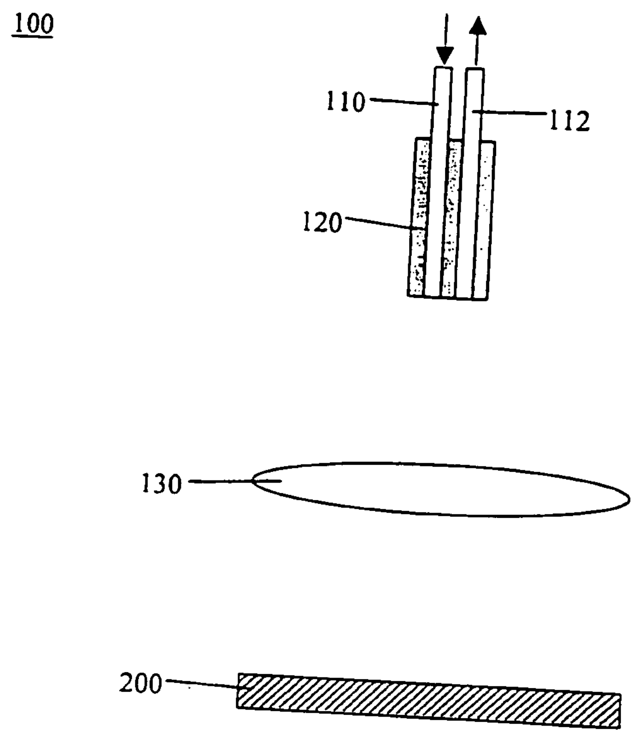

FIGURE 1

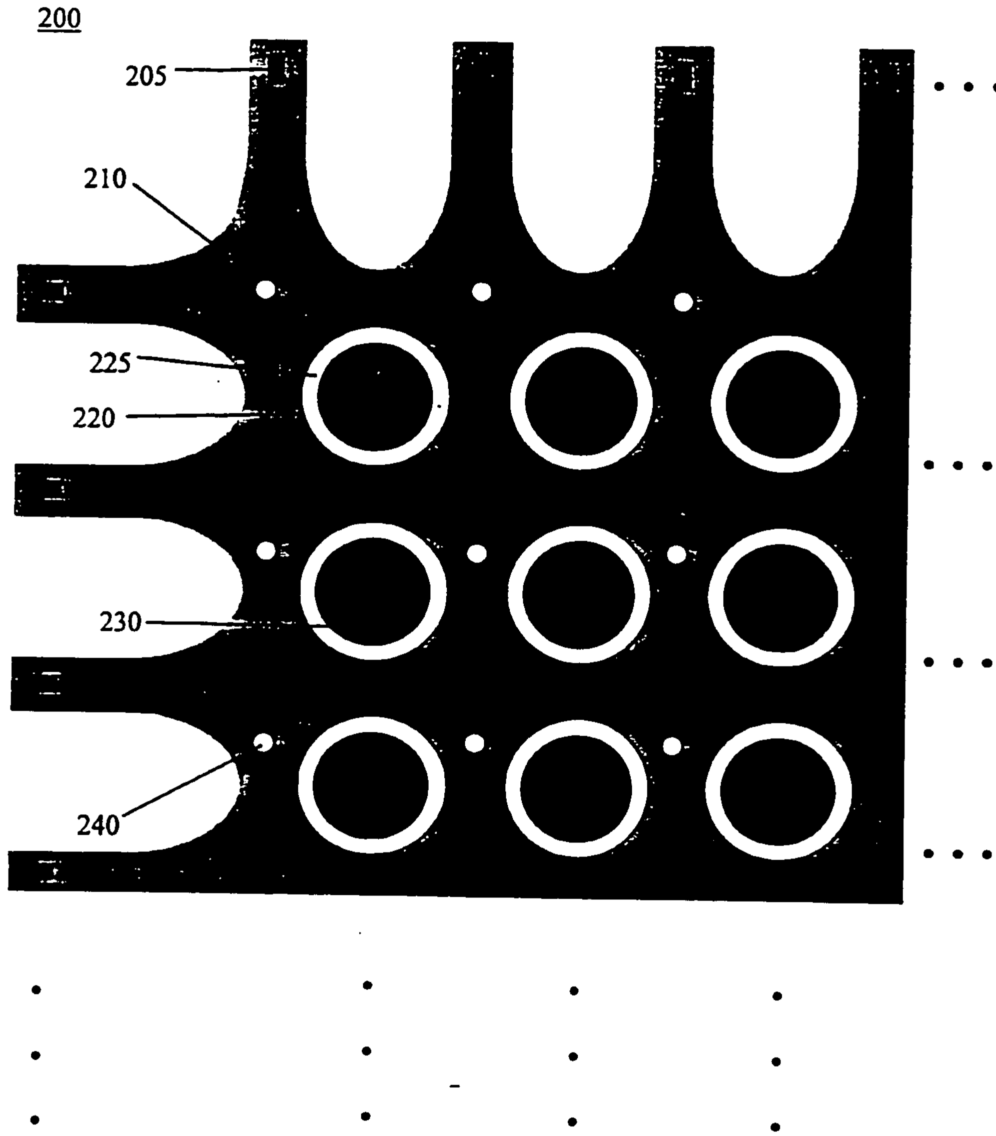

FIGURE 2A

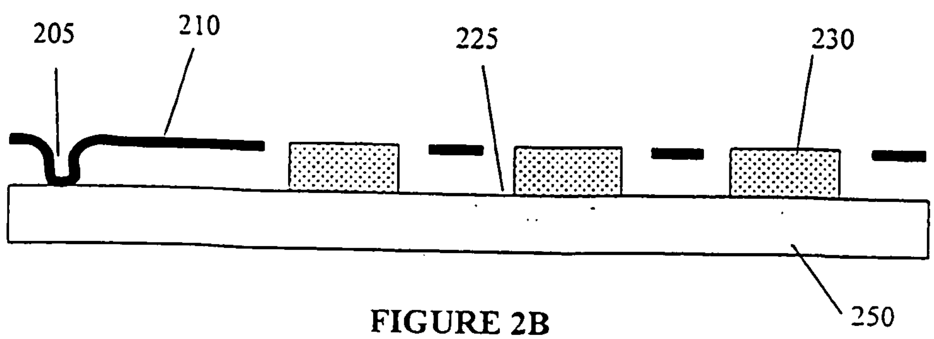

FIGURE 2B

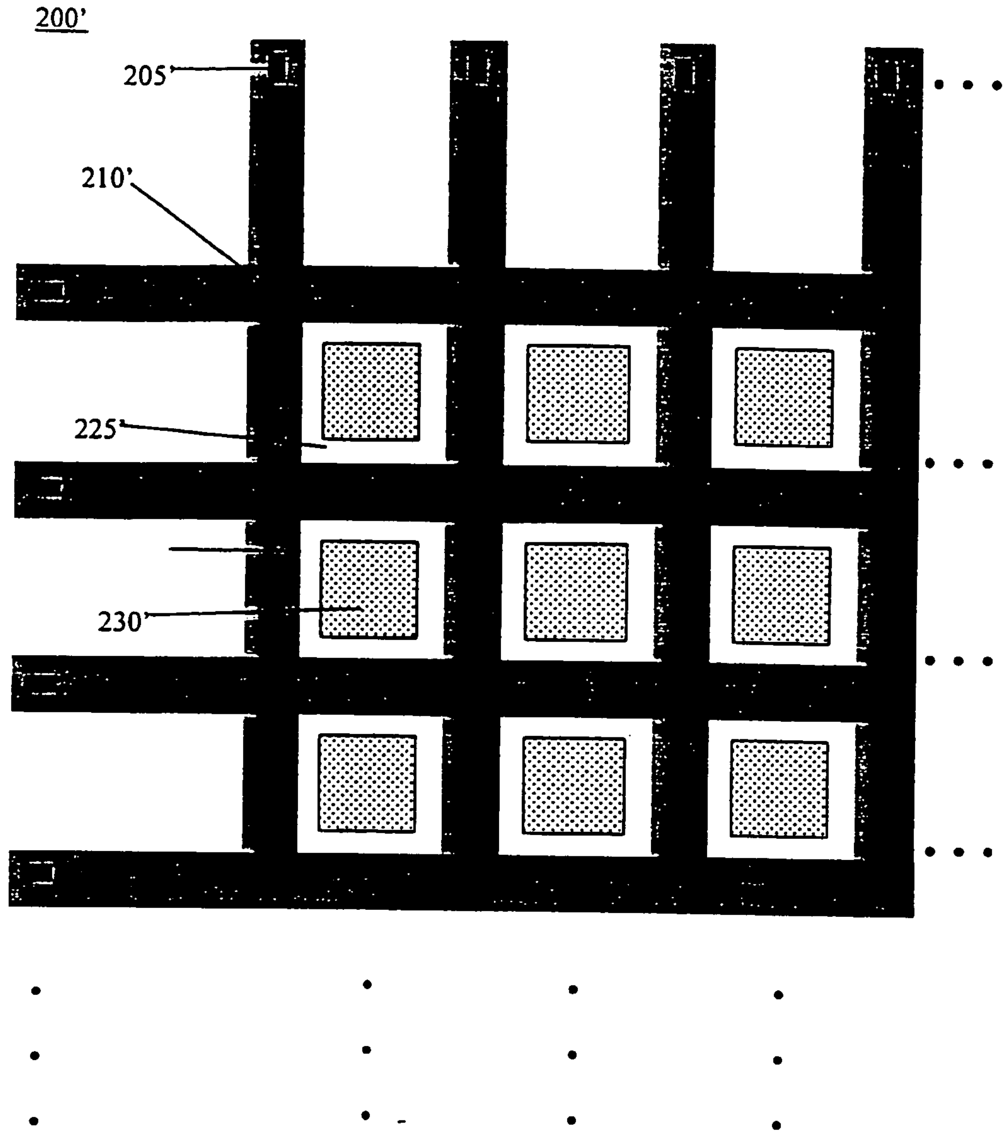

FIGURE 3A

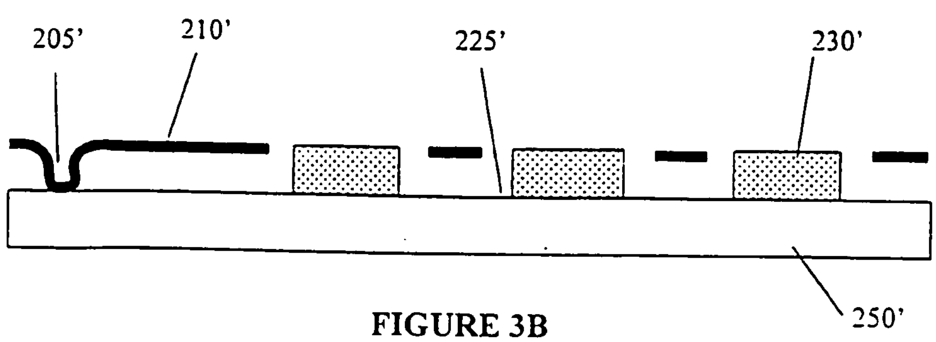

FIGURE 3B

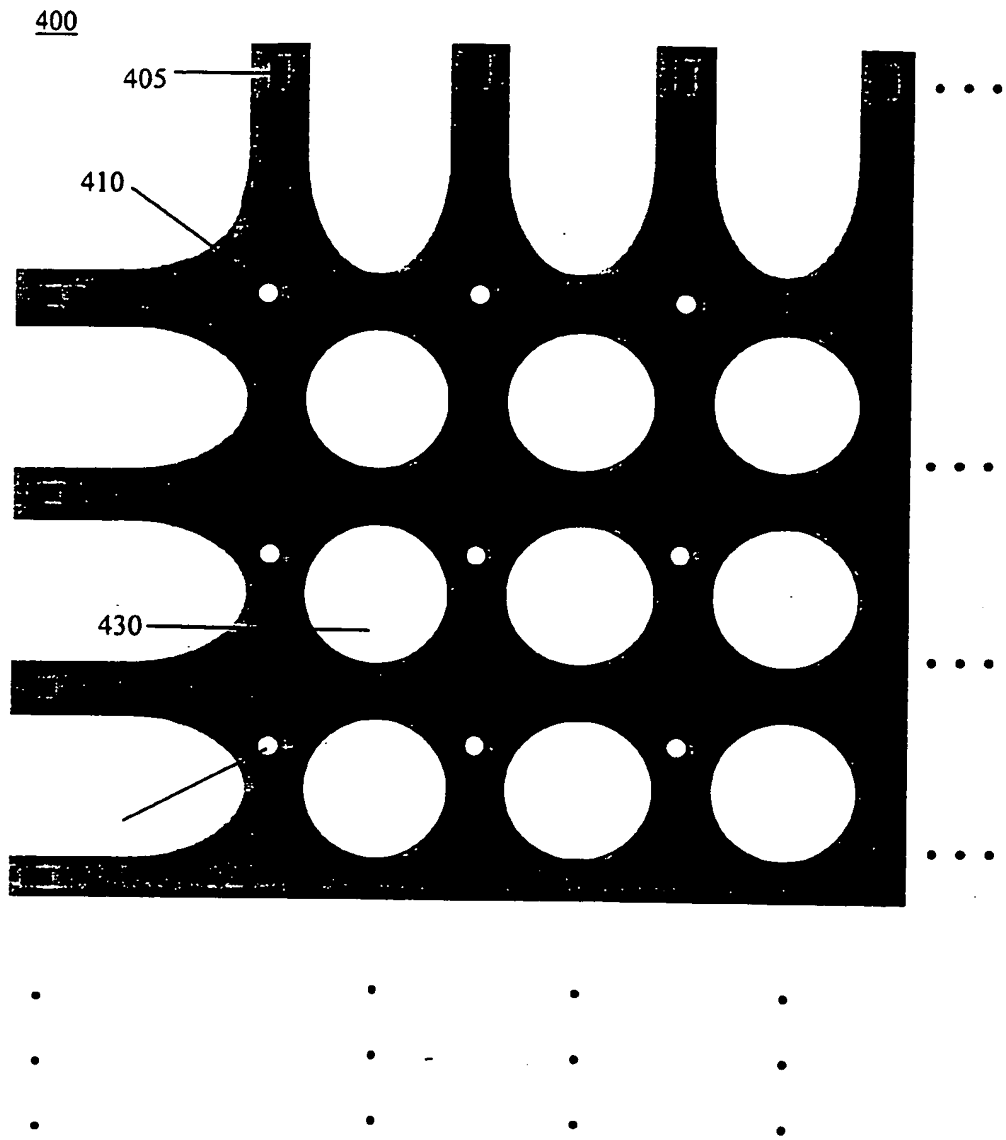

FIGURE 4A

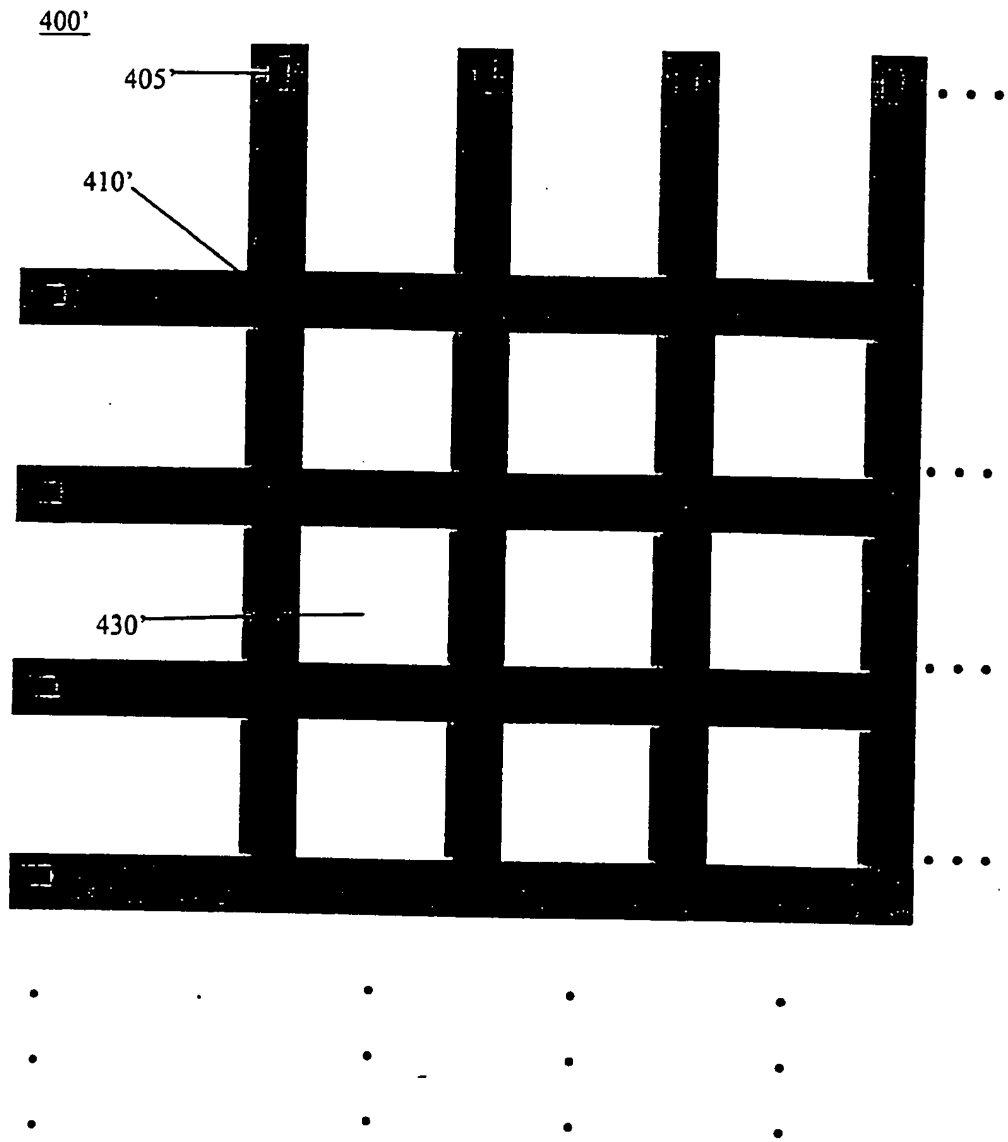

FIGURE 4B

200

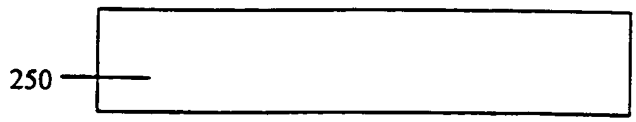

FIGURE 5A

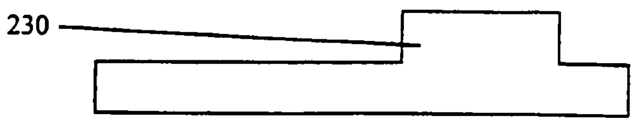

FIGURE 5B

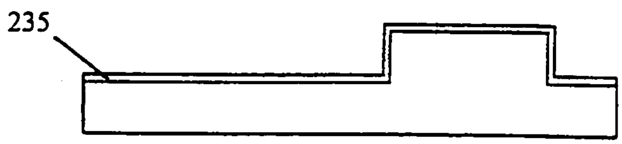

FIGURE 5C

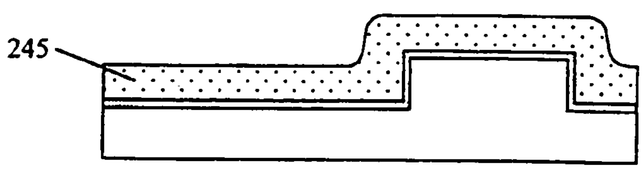

FIGURE 5D

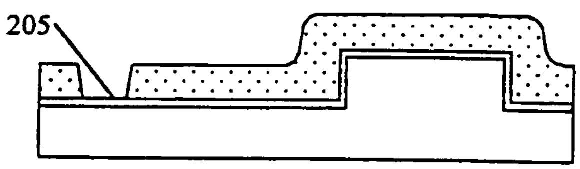

FIGURE 5E

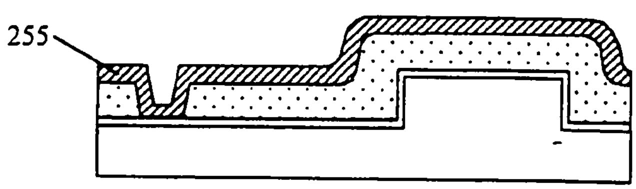

FIGURE 5F

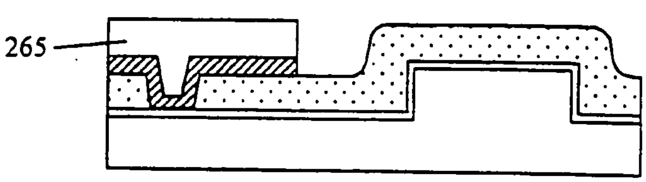

FIGURE 5G

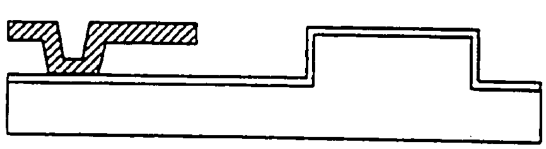

FIGURE 5H

INTERNATIONAL SEARCH REPORT

Inte. .onal Application No
PCT/US 00/21647

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B5/18 G02B26/08 G02B6/34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 420 416 A (IIDA MASANORI ET AL) 30 May 1995 (1995-05-30) column 6, line 15 -column 9, line 4 abstract; figures 1,2 ---	45
X	PATENT ABSTRACTS OF JAPAN vol. 013, no. 395 (P-927), 4 September 1989 (1989-09-04) -& JP 01 142505 A (MATSUSHITA ELECTRIC IND CO LTD), 5 June 1989 (1989-06-05) abstract; figures 1,2 ---	45
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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
14 November 2000	24/11/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Narganes-Quijano, F

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